FOIL FUSES AS OPENING SWITCHES FOR SLOW DISCHARGE CIRCUITS

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Summary

Metal foil fuses embedded in various materials are widely used as opening switches in fast discharge circuits (~1 μs). Several technologies of current interest require opening switches in circuits which operate on a much longer time scale (~100 μs). We have investigated the behavior of aluminum and copper foil fuses for conduction times of 100-200 μs. Reliable current interruption is obtained at the end of melting rather than at the end of vaporization. The ratio of initial to final resistance is > 100. In general, the performance of slow fuses can be predicted by simple scaling from fast fuse behavior. For applications where the switching function depends critically on the resistivity versus input energy characteristic, the results presented can be used in the selection of proper fuse size and geometry.

Introduction

The use of metal foils and wires for circuit interruption and switching is well known [1,2,3,4] for conduction periods of a few microseconds or less. On this time scale, the behavior of fuses is similar to that of exploding wires, which have been extensively investigated. Typically, as the fuse is heated, it passes from solid to liquid phase and finally to the vapor phase where the resistivity becomes very high. As the heating rate is increased, the fuse resistivity is observed to decrease for a given energy input, sometimes by as much as a factor of three [5].

When the conduction time is increased by a factor of 10-100, new physical effects enter the picture, e.g., bulk motion of the foil under magnetic or surface tension forces. Thus, it is not unexpected that the details of fuse behavior will be different for long conduction times. The principle difference which we have identified is the onset of high resistivity at the end of the melting phase, well before the fuse material has been heated to the vaporization temperature.

Despite the early onset of high resistivity, the total energy capacity of the fuse before restrike is still comparable to the total vaporization energy. The physical behavior of the fuse immediately after melting is not yet understood. Several experiments reported below offer insight into the mechanism responsible for the high resistivity in the molten phase.

Experimental Arrangement

All of the experiments were performed using the circuit shown in Fig. 1. In this circuit, the fuse element is normally sized to conduct current from the time switch S_2 is closed until peak current occurs at 190 μs. Then the crowbar switch S_1 is closed and the fuse operates to interrupt the current in the primary circuit and to dissipate the energy stored in the stray inductance, L_S. In this application, the fuse is operated as a non-linear resistor to damp oscillation of the primary circuit. Typical operating conditions are: 12 kV charge, 110 kA peak current and a fuse dissipation of 6-10 kJ.

A fuse element, installed in its enclosure, is shown in Fig. 2. The enclosure is made of G-10 fiberglass-epoxy. The fuse is clamped at each end by a brass bar which defines the active length of 12.4 cm. The interior of the enclosure, 15.2 x 10.2 x 5.1 cm^3, is normally filled with "playbox" sand from the local building material supplier. The lid has a 1.3-cm-thick piece of heavy rubber foam mounted on it to apply pressure to the sand and maintain uniform contact between sand and fuse. The enclosure lid is well secured because abnormal interruption (energy dissipation>>vaporization energy) can result in very high internal pressures.

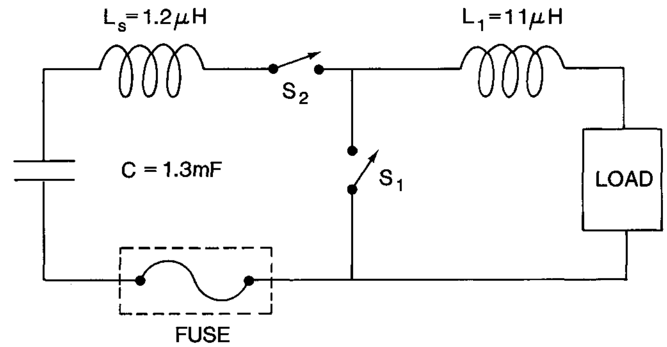

Fig. 1. Schematic of Fuse Test Circuit

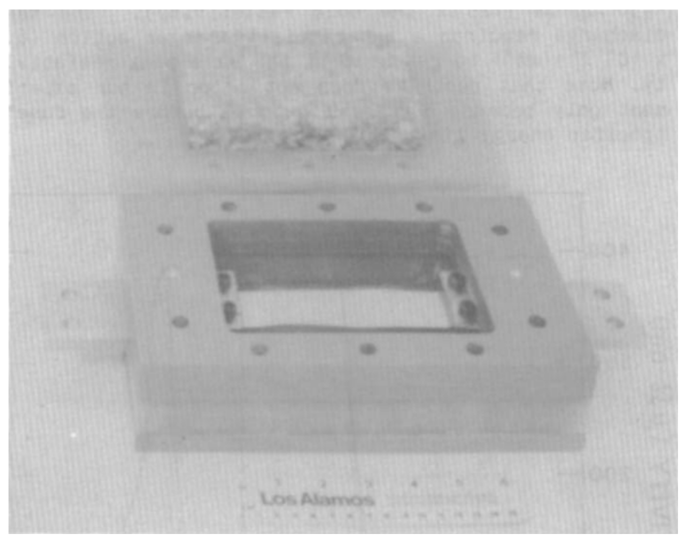

Fig. 2. Photograph of Fuse in Holder During Assembly

Experimental Results

Fuse Resistance

Figure 3 shows typical operating waveforms for a 110 kA discharge. The fuse element is 1100 series aluminum with dimensions 0.02 x 2.9 x 12.4 cm^3. The fuse element develops a voltage of 8.7 kV by the time switch S_1 operates. The fuse current decays in 14 μs (1/e) and exhibits a period of reverse conduction before recovering to a high resistance state with a reverse voltage of 900 V.

The pronounced difference between slow and fast fuse behavior is easily seen in Fig. 4 where the data of Fig. 3 have been converted to a plot of resistivity versus specific action, g, where

$$g = \int I^2 dt / A^2$$

and A is the cross-sectional area of the fuse. The

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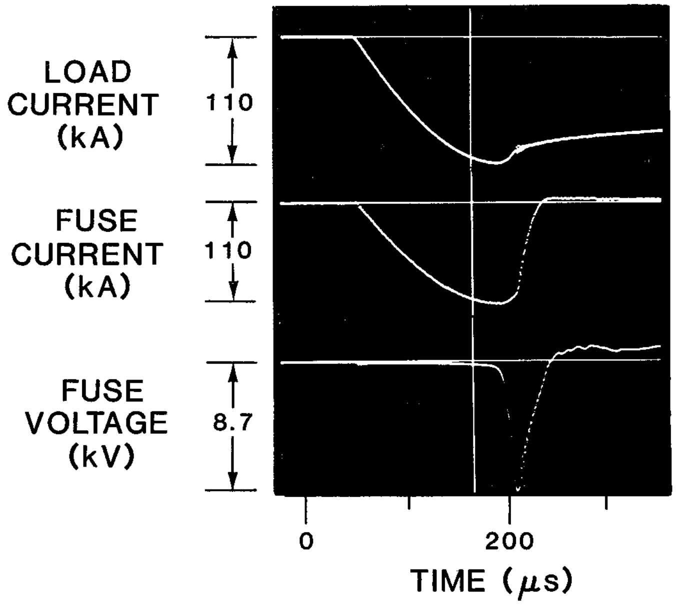

Fig. 3. Typical Current and Voltage Waveforms

dotted curve in Fig. 4, taken from Reference 6, shows the fast time behavior measured for aluminum wires exploded on a microsecond time scale. The resistivity is identical until the end of melting, when the resistivity of the aluminum foil rises abruptly to ~350 $\mu\Omega$/cm (125 x the cold resistivity). The fast discharge requires a substantially larger action (6.5 x 10^4 A^2s/mm^4) to reach about the same peak resistivity. Note that restrike does not occur in our experiment only because current flow ends before the fuse's specific energy limit is reached.

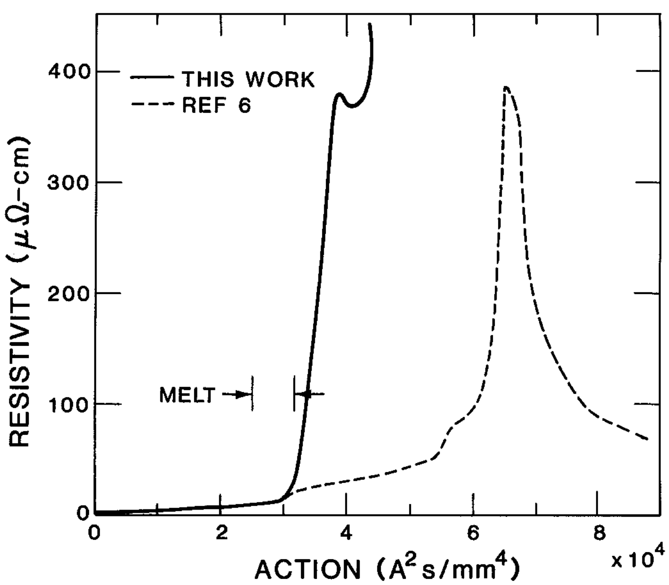

Fig. 4. Resistivity vs. Action, Aluminum Fuse in Sand

Figure 5 compares identical fuses surrounded by air, sand, and a solid of density 3.9 g/cm^3. The fuse in air does not reach high resistance and goes over to a low resistance restrike. The fuse embedded in a solid is prevented, to some extent, from undergoing motions which the sand permits. The onset of high resistivity is modified by this constraint but it is not delayed until vaporization.

The result shown in Fig. 5 suggests that physical motion plays a role in the early onset of resistivity.

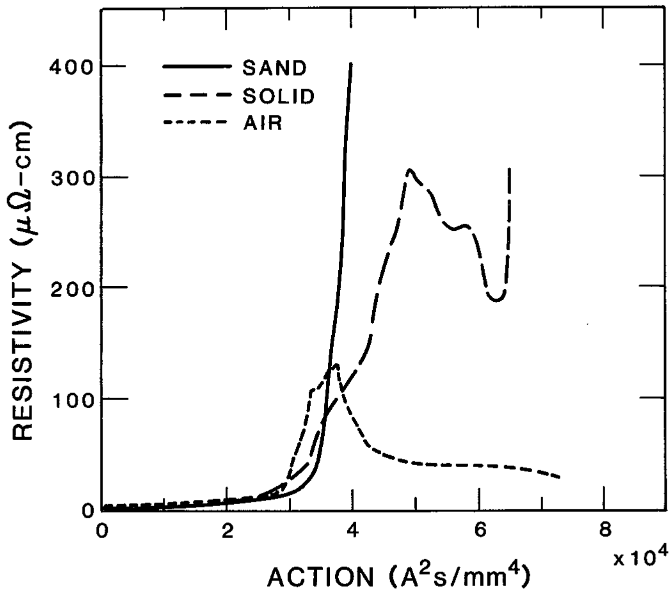

Fig. 5. Effect of Surrounding Material, Aluminum Fuse

The only force acting on the fuse which appears to be strong enough to cause meaningful motion (a few times the foil thickness) on a 10-μs time scale is the self-magnetic force. For a flat foil, this force acts in the plane of the foil pushing the edges toward the center. The force on the edge is very high, decreasing to zero at the center. If this picture is valid, then a cylindrical fuse element, which has a uniform, radial force, should exhibit a faster, cleaner interruption. Figure 6 compares the voltage versus time behavior for two identical fuse elements, one flat, the other formed into a cylinder with sand inside and outside. The onset of resistance is sharper for the cylindrical foil and the peak voltage is 30% higher.

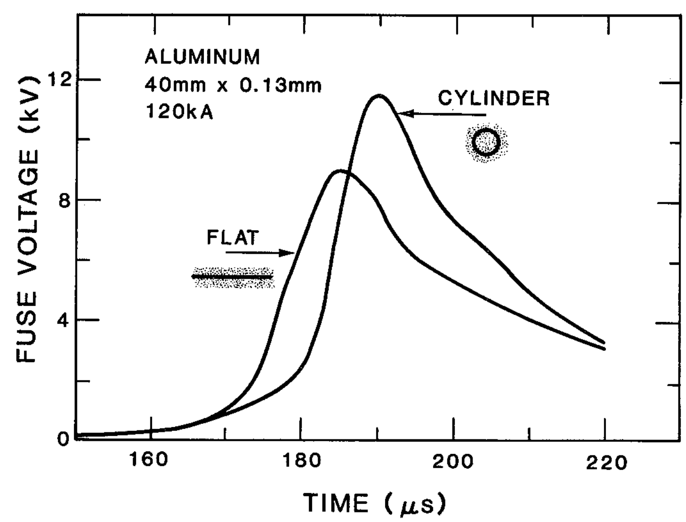

Fig. 6. Effect of Fuse Geometry on Switching

Figure 7 is another comparison of different foil geometries. In this case, one foil is flat and the other has been folded in half lengthwise three times to form a "wire". Both the "wire" and the foil exhibit similar resistance versus time. Interruption by the "wire" fuse at the melting point is not unexpected because the surface magnetic field is about 15 T and the liquid column is subject to pinch instabilities on a 10 μs time scale.

A limited investigation was carried out of other parameters which could affect fuse performance. Fig-

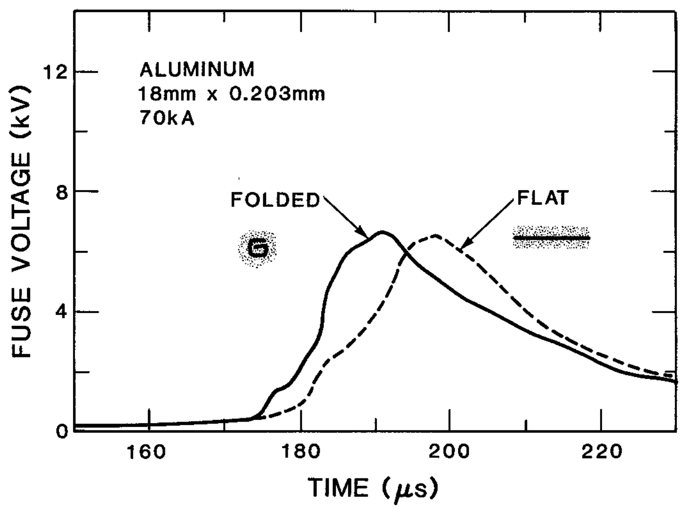

Fig. 7. Effect of Fuse Geometry on Switching

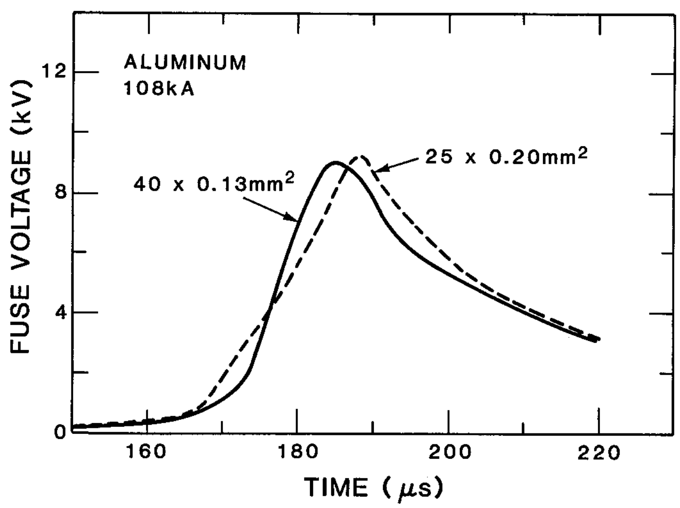

Fig. 8. Effect of Foil Thickness on Switching

ure 8 compares two fuses of equal cross-sectional area but different thickness. The thinner foil has a faster voltage increase, 700 V/μs, compared to 400 V/μs for the thicker foil but the peak resistivity is not affected.

Figure 9 is a plot of resistivity versus action for copper. Again, high resistivity is measured immediately after melting.

Figure 10 compares flat aluminum and copper foils whose thicknesses are chosen to give interruption at the same time on the current waveform. The copper fuse has a sharper rise and higher peak resistance. Some of this difference may be due to the thickness effect discussed previously.

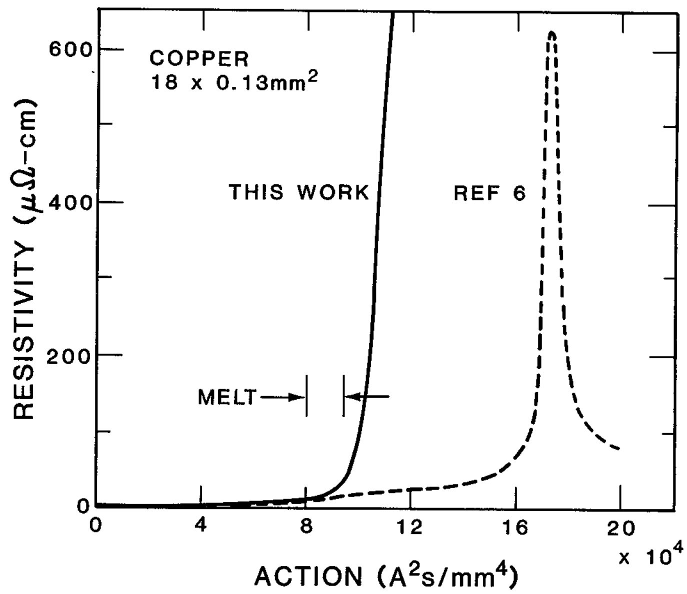

Fig. 9. Resistivity vs. Action, Copper Fuse in Sand

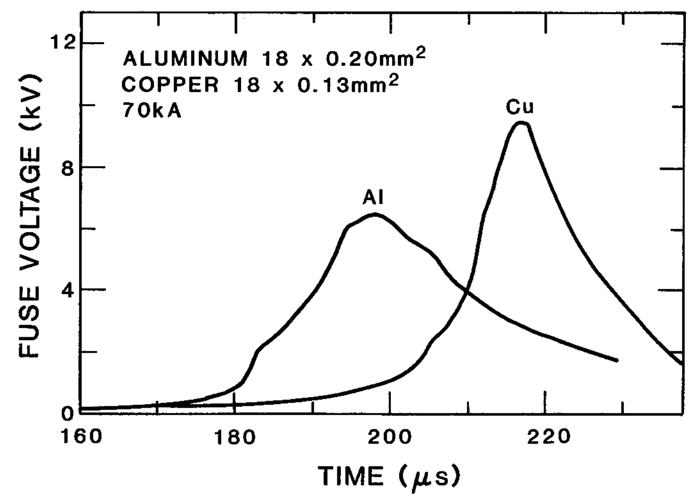

Fig. 10. Comparison of Copper and Aluminum Fuses

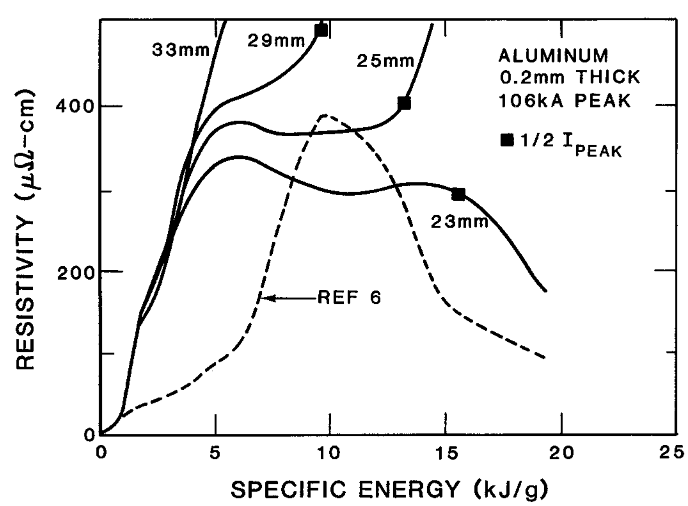

Fig. 11. Resistivity vs. Specific Energy, Aluminum Fuses in Sand

Energy Dissipation

An important parameter in the design of fuses for circuit interruption is the energy which the fuse must dissipate during the interruption process. If the total energy is greater than the fuse's capability, restrike will occur. For applications requiring voltage hold-off after interruption, restrike must be avoided. The energy handling capability of aluminum foil fuses was investigated by varying the fuse width at constant current. Narrow fuses interrupt before switch S_1 closes and the fuse is forced to dissipate some of the energy stored in the load inductor L_1. Figure 11 shows the resistivity versus specific energy for four fuse widths. On each curve, the point where the current decreases to one-half of peak is marked. The 29- and 33-mm fuses exhibit rapidly increasing

resistance as the current decays. At 25 mm, the fuse exhibits a wide region of nearly constant resistance but finally recovers to high resistance as the current decays. The 23-mm fuse, in contrast, goes into a low resistance restrike mode. The limiting specific energy for this particular fuse geometry is 13-15 kJ/g. The dashed curve, taken from Reference 6, shows the behavior measured for fast discharges. In this case, the specific energy before restrike is 10 kJ/g, comparable to our value for a slow fuse.

This result suggests that, whatever the difference between slow and fast fuse behavior at early time, the end point is still associated with complete vaporization of the fuse material.

Recovery Voltage

Due to limitations of time and equipment, no experiments were carried out to directly address recovery voltage. In the course of our measurements, it was observed that recovery voltage decreases with time after interruption. For 100-200 μs after current zero, an electric field of 100-120 V/cm can be sustained without conduction. After 500 μs, the maximum field is generally 75-80 V/cm, a value which is sustained for the duration of our measurement (2000 μs).

Switching Time

The switching time for a fuse is a function principally of the peak fuse resistivity and the specific energy capacity of the fuse material. For inductive switching, it can be shown that the switching time is a fixed fraction of the conduction time given by

$$\frac{t_s}{t_c} = \frac{2\, E_s\, \delta}{\zeta_m\, g} \qquad (1)$$

where E_s = maximum specific energy (J/g)

δ = density (g/cm^3)

ζ_m = peak resistivity (Ω-cm)

g = action at max. resist. ($A^2 s/cm^4$)

t_s = switching time

$t_c = \int_0^{t_o} I^2 dt \,/ I_o^2$

where t_o is the time switching occurs. For a sinusoidal waveform, t_c is one-half of the quarter cycle time.

Using the values appropriate for fast fuses, Equation 1 gives t_s/t_c = 0.20. This compares well with measured values of 0.25-0.32 [3,4]. When the appropriate values for slow fuses are used in Equation 1, the result is t_s/t_c = 0.16, somewhat smaller than for fast fuses. Our measured switching times are 0.22-0.27, in reasonable agreements with this simple scaling relation.

For fast switching, the specific energy should be limited to 5-6 kJ/g. This results in the highest resistance as seen in Fig. 11. This is a significant difference from fast fuses where fast switching requires a specific energy of 9-10 kJ/g.

Conclusion

Foil fuses surrounded by sand are useful as opening switches on a 100-μs time scale. Some of the parameters characterizing slow fuses are similar to fast fuses, e.g. peak resistivity, maximum energy capability and the ratio of switching time to conduction time. The principal difference is the action value for peak resistance which is about one-half as large for slow fuses.

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References

[1] H.C. Early and F.J. Martin, "Method of Producing a Fast Current Rise from Energy Storage Capacitors", Review of Scientific Instruments, v. 36, pp. 1000-1002, July 1965

[2] Ch. Maisonnier, J.G. Linhart, and C. Gourlan, "Rapid Transfer of Magnetic Energy by Means of Exploding Foils", Review of Scientific Instruments, v. 37, pp. 1380-1384, October 1966

[3] J.N. DiMarco and L.C. Burkhardt, "Characteristics of a Magnetic Energy Storage System Using Exploding Foils", Journal of Applied Physics, v. 41, pp. 3894-3899, August 1970

[4] R.E. Reinovsky, et.al., "Inductive Store Pulse Compression Systems for Driving High Speed Plasma Implosions", IEEE Transactions on Plasma Sciences, v. PS-10, pp. 73-81, June 1982

[5] T.J. Tucker, "Behavior of Exploding Gold Wires", Journal of Applied Physics, v. 32, pp. 1894-1900, October 1961

[6] T.J. Tucker and R.P. Toth, "EBW1: A Computer Code for the Prediction of the Behavior of Electrical Circuits Containing Exploding Wire Elements", Sandia Laboratories Report #SAND-75-0041, April 1975